NOLTR 63-78

THE USE OF AUTOFRETTAGED LOOSE
BARREL LINER CONSTRUCTION FOR
HYPERVELOCITY LAUNCHERS

NOL

15 MAY 1963

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

18

UNCLASSIFIED
NOLTR 63-78

Ballistics Research Report 99

THE USE OF AUTOFRETTAGED LOOSE BARREL LINER
CONSTRUCTION FOR HYPERVELOCITY LAUNCHERS

Prepared by:
V. C. D. Dawson and A. E. Seigel

ABSTRACT: The use of gun-type hypervelocity launchers in
aerodynamic research and development has placed a severe
problem on the designer of these devices. The extremely
high muzzle velocities (12,000 feet per second to 30,000
feet per second) attained increase the barrel erosion and
wear to such levels that a very low firing life is available.
Thus, the cost of employing these launchers in a research
program, because of high replacement costs and low life
expectancy, becomes excessive. This report treats the
possibility of using the loose liner barrel construction
as a means of reducing these costs and shows that employment
of autofrettaged liners offers distinct advantages.

PUBLISHED SEPTEMBER 1963

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

i
UNCLASSIFIED

THE USE CF AUTOFRETTAGED LOOSE BARREL LINER CONSTRUCTION FOR HYPERVELOCITY LAUNCHERS

R. E. ODENING
Captain, USN
Commander

R. Kenneth Lobb

R. KENNETH LOBB
By direction

CONTENTS

ILLUSTRATIONS

Figure   Title

1   Internal Pressure Required to Yield Liner as a
             Function of Initial Liner - Jacket Clearance

2   Internal Pressure Required to Yield a Fully
             Autofrettaged Liner as a Function of Initial
             Liner Clearance

REFERENCES

(1) Dawson, V. C. D., "Elastic and Plastic Stress Equations
for Hollow Cylinders and Spheres Subjected to Internal
and External Pressure," NavOrd Report 6786, 4 Feb 1960

(2) Dawson, V. C. D. and Seigel, A. E., "Reverse Yielding
of a Fully Autofrettaged Tube of Large Wall Ratio,"
NOLTR 63-123 (in preparation)

LIST OF SYMBOLS

P	Pressure (psi)
P_c	Pressure to take up clearance
P_f	Pressure to cause yielding
Y_o	Yield strength (psi)
ω	Wall ratio (outside diameter/inside diameter)
σ	Stress (psi)
δ	Clearance (in)
E	Young's modulus (30×10^6 psi)
D_o	Outside diameter (in)
S	Distortion energy stress (psi)
ε	Strain (in/in)
ε_{tc}	Tangential strain to take up clearance

Subscripts

t	Tangential
z	Longitudinal
r	Radial
ℓ	Liner

INTRODUCTION

One of the most serious difficulties encountered in the use of hypervelocity launchers is that of barrel wear. To attain velocities above 15,000 feet per second the finish and straightness tolerances on the launch tube are necessarily very restrictive. The launching of fragile sabot-model combinations at these hypervelocities requires these restrictive tolerances. Because of the high temperature, pressure and velocity of the propelling gases, the wear on the barrel becomes excessive. This wear takes the form of washed-out (eroded) areas, ridges, grooves, etc. The development of such areas within the tube seriously limits the performance since they create transverse accelerations, gas blowby and axial sabot impacts. Thus, the maximum velocity that can be obtained from the launcher decreases as it wears.

Various techniques have been employed at the Naval Ordnance Laboratory to minimize this problem, e.g., nitriding of the bore surface, adjusting the alloy content of the steel to provide better wear characteristics, etc. While all of these measures may provide minor benefit, they do not materially extend the tube life. After a certain number of shots (of the order of 50 to 200 depending on the velocities) barrel erosion is so severe that the tube must be replaced.

Since the existing barrels cost up to $55,000 to manufacture and require a lead time of up to six months, it is apparent that considerable preplanning and budgeting are required to maintain a coherent firing schedule. In addition, the depreciation adds considerable cost to each shot made with the launcher.

One of the methods employed during World War II to decrease the cost of barrel wear was to employ loose liners. The idea is to insert a thin liner having sufficient diametral clearance into a thick outer cylinder. On firing, the tube swells sufficiently to be reinforced by the outer tube. When the wear increases to an excessive amount, the liner is slipped out and replaced by a new liner. Thus, the cost of replacement is only the liner cost.

In the section below the limitations of this process will be studied.

LOOSE LINER CONSTRUCTION

In all of the design work on a hypervelocity launcher, the limit criterion is based upon yielding of the tube. When

1

yielding begins at the inside diameter, a residual permanent
set occurs in the bore. The resultant non-uniform bore diameter
results in undesirable gas blowby and sabot acceleration.

Based upon the Distortion Energy Theory, yielding at the
bore occurs when*

$$P = \frac{Y_0 \, (\omega^2 - 1)}{\sqrt{3} \quad \omega^2} \tag{1}$$

Thus, an infinite wall ratio tube will yield at a pressure
given by

$$P = \frac{Y_0}{\sqrt{3}} \tag{2}$$

If the wall ratio is less, say in the range $\omega = 1.1$ to 1.7
the pressure capability (from eq. (1)) varies from $.174 \, Y_0/\sqrt{3}$
to $.655 \, Y_0/\sqrt{3}$. Thus, the pressure capability of any tube is
restricted to relatively low values for elastic operation.

In loose liner construction, the inner tube having a
relatively low wall ratio (since otherwise no cost saving would
occur on replacement) is inserted into a thicker-walled jacket.
When pressure is applied the liner expands and takes up the
clearance until it is supported by the outer jacket. The entire
tube then acts as a thick-walled tube as additional pressure is
applied. Thus, the tube initially acts as a thin-walled tube
until the pressure causes contact with the outer tube. If the
yield point of the liner is reached at any time during the entire
pressurization it will permanently expand and be left with a
residual set. If, in this case, the clearance is used up, the
liner cannot be easily removed and the entire purpose of the
loose construction is defeated.

Now the outside diameter D_0 swells elastically by an
amount δ as given by the equation

$$\delta = D_0 \, \varepsilon_{t_{\ell_0}} = D_0 \, \frac{1.7 \, P}{E \, (\omega_\ell^2 - 1)} \tag{3}$$

----

* This result is for a closed-end tube. The result for the
open or plane strain case does not vary more than a few
percent from this value. Equation (1) for the closed-end
tube is based upon the yield condition $\sigma_t - \sigma_r = 2Y_0/\sqrt{3}$.

Thus, if the liner has a given clearance, δ on the diameter, the pressure at which the liner engages the jacket is

$$P_c = \frac{\delta E (\omega_\ell^2 - 1)}{D_0 \; 1.7} \tag{4}$$

At this pressure, the combined stress (by the Distortion Energy Theory) at the bore is

$$S_1 = \sqrt{3} \; P_c \; \frac{\omega_\ell^2}{\omega_\ell^2 - 1} \tag{5}$$

If additional pressure is now applied to the liner-jacket combination, the liner bore will eventually reach the yield point. This limit occurs when an additional ΔP has been applied which is given by the yielding condition

$$S_1 + \frac{\sqrt{3} \; \Delta P \; \omega^2}{\omega^2 - 1} = Y_0^{*} \tag{6}$$

where ω is the over-all wall ratio of liner and jacket ($\omega = \omega_j \, \omega_\ell$).

Substituting $\Delta P = P_f - P_c$ and $S_1 = \frac{\sqrt{3} \; P_c \; \omega_\ell^2}{\omega_\ell^2 - 1}$ into equation (6) gives

$$\frac{\sqrt{3} \; P_c \; \omega_\ell^2}{\omega_\ell^2 - 1} + \frac{\sqrt{3} \; \omega^2}{\omega^2 - 1} \left(P_f - P_c \right) = Y_0$$

or

$$P_f = \frac{\omega^2 - 1}{\sqrt{3} \; \omega^2} Y_0 + P_c \left[1 - \frac{\omega_\ell^2 (\omega^2 - 1)}{\omega^2 (\omega_\ell^2 - 1)} \right] \tag{7}$$

----

* The yield criterion for the closed-end tube where it is assumed $\sigma_z = (\sigma_t + \sigma_r)/2$, reduces to $\sigma_t - \sigma_r = 2 Y_0 / \sqrt{3}$ which is equivalent to equation (6).

3

By virtue of equation (3)

$$\frac{P_f}{Y_o} = \frac{\omega^2-1}{\sqrt{3}\,\omega^2} \;-\!-\!- \; \frac{E\,\varepsilon_{tc}}{1.7\,Y_o}\left(\frac{\omega^2-\omega_\ell^2}{\omega^2}\right) \qquad (8)$$

Equation (8) gives the maximum value of pressure that a loose liner construction will hold elastically for any value of Y_o, E, ε_{tc}, ω_ℓ and ω. For greater values of pressure, the bore of the liner will be plastically yielded. Figure 1 is a plot of P_f/Y_o against $E\,\varepsilon_{tc}/Y_o$ for various values of ω_ℓ. The assumed value of ω is 5 for the plot.* If the clearance is zero, the liner and jacket will act as a tube of wall ratio 5; thus, the value of P_f/Y_o is from equation (1)

$$\frac{P_f}{Y_o} = .554$$

As $E\,\varepsilon_{tc}/Y_o$ increases, i.e., clearance between liner and jacket is permitted, the value of P_f/Y_o decreases. For each value of ω_ℓ there is a limiting value of $E\,\varepsilon_{tc}/Y_o$ indicated by the horizontal dotted portion of each curve. At this limiting value, the liner just reaches the yield point as the clearance between tube and liner reaches zero. Further pressurization will cause yielding of the liner. An interesting feature of figure 1 is the very small dependence that P_f/Y_o has on ω_ℓ. Essentially all the curves coincide except for the limiting value.

It is apparent from figure 1 that the introduction of clearance seriously degrades the pressure to which the system can operate elastically. For example, consider the following case:

----
* For ω large, equation (8) becomes

$$\frac{P_f}{Y_o} = \frac{1}{\sqrt{3}} \;-\!-\!- \; \frac{E\,\varepsilon_{tc}}{1.7\,Y_o}$$

The plot in figure 1 for $\omega = 5$ is in good agreement with this equation.

Steel Liner   I.D.   1.00" $Y_0 = 140,000$ psi

Liner   O.D.   1.30"

Clearance on diameter   .002"

$$\epsilon_{tc} = \frac{.002}{1.30}, \qquad \frac{E\epsilon_{tc}}{Y_0} = \frac{30 \times 10^6}{140 \times 10^3} \frac{.002}{1.30} = .32$$

From figure 1, $P_f/Y_0 = .375$ or $P_f = 52,500$ psi.

If the clearance were zero, i.e., monobloc construction had been used, the peak pressure that could be maintained, from figure 1 ($E\epsilon_{tc}/Y_0 = 0$), would be 77,500 psi. Thus, the loose liner construction degraded the pressure capability by 32 percent.

Thus, although while the loose liner provides a low-cost method of barrel replacement it suffers from the serious drawback that the pressure capability is limited.

AUTOFRETTAGED LOOSE LINER CONSTRUCTION

From equation (1), for very large wall ratios, the limiting pressure is $Y_0/\sqrt{3}$. Thus, to attain a pressure of 100,000 psi elastically it is necessary to use a steel having a yield of 173,000 psi. The problem of obtaining a chamber of large size with such a yield strength is considerable. Thus, to obtain high-pressure operation such as is required in hypervelocity development, it is necessary to resort to other methods than straight monobloc construction. These methods are the use of compound tubes with interference construction (shrink fits) or the autofrettaging of a monobloc tube (ref. (1)). This last technique is the one most often applied in the design of launchers at the Naval Ordnance Laboratory. The autofrettage principle is based upon pressurizing a cylinder to values greater than the pressure that causes yielding initiation at the bore. This pressure application causes yielding through part or all of the wall depending upon the pressure applied. The non-uniform yielding produces residual compressive stresses at the bore so that pressure can subsequently be applied up to the autofrettage pressure with the cylinder reacting elastically.

To obtain the high pressures required in hypervelocity experiments, the autofrettage process is applied during manufacture of the tube. There is a limit to the pressure that a tube can be subjected to during this process. The limit is

$$P = \frac{2 Y_0}{\sqrt{3}} \ln \omega, \qquad \omega \leq 2.22^{*} \quad (9)$$

$$P = \frac{2 Y_0}{\sqrt{3}} \frac{\omega^2 - 1}{\omega^2}, \qquad \omega \geq 2.22^{**} \quad (10)$$

For the larger wall ratios, from equation (10) the pressure is twice the pressure given by equation (1). The autofrettage process has, therefore, doubled the pressure capability of the system for elastic operation.

While a gain has been obtained in pressure capability, no advantage has been obtained as far as wear is concerned. In fact, autofrettaged tubes cannot be rebored without reducing their pressure capability since some of the residual stresses are removed during reboring.

The advantages of autofrettage in monobloc construction, as indicated above, lead one to consider whether such a process might not lend itself to loose liner construction. The idea here is that the loose liner, which of necessity has a relatively small wall ratio, would be pressurized to the fully plastic state during manufacture. Thus, its elastic pressure range would be increased over what it would have been in the non-autofrettaged condition. It would then be inserted into a jacket under the same conditions as given in the second section of this report. The feasibility of this procedure will now be investigated.

The pressure required to make the liner fully plastic is from equation (9)

$$P = \frac{2 Y_0}{\sqrt{3}} \ln \omega_\ell \qquad (11)$$

----

* At the pressure given by equation (9) the tube becomes fully plastic (see reference (1)).
** At the pressure given by equation (10) for $\omega \geq 2.22$ the residual stresses are of such magnitude that the bore is on the verge of yielding in compression (see reference (1)). Also see reference (2) for use of reyielded tubes.

After application of this pressure to the liner, the liner is described as fully autofrettaged, and subsequent application of pressure up to this value will cause only elastic deformations of the liner.

This pressure induces residual stresses at the bore which are (see reference (1))

$$\sigma_t^* = \frac{2Y_o}{\sqrt{3}} - \frac{4Y_o\,\omega_\ell^2}{\sqrt{3}\,(\omega)_\ell^2 - 1} \ln \omega_\ell \qquad (12)$$

$$\sigma_r^* = 0 \qquad (13)$$

The pressure required to take up the clearance δ between the liner and jacket is

$$P_c = \frac{\delta E(\omega_\ell^2 - 1)}{D_o\ \ 1.7} = \varepsilon_{t_c} E \frac{\omega_\ell^2 - 1}{1.7} \qquad (4)$$

and it produces stresses in the bore

$$\sigma_t = P_c \frac{\omega_\ell^2 + 1}{\omega_\ell^2 - 1} \qquad (14)$$

$$\sigma_r = -P_c \qquad (15)$$

The stresses produced by application of additional pressure to the liner-jacket combination are

$$\sigma_t = \Delta P \frac{\omega^2 + 1}{\omega^2 - 1} \qquad (16)$$

$$\sigma_r = -\Delta P \qquad (17)$$

7

where

$$\Delta P = P_f - P_c$$

By superposition of all the stresses the yield condition gives

$$\frac{2Y_o}{\sqrt{3}} = \sigma_t - \sigma_r = \Delta P \left(\frac{\omega^2+1}{\omega^2-1}\right) + P_c \frac{\omega_\ell^2+1}{\omega_\ell^2-1}$$

$$- \frac{4Y_o}{\sqrt{3}} \left(\frac{\omega_\ell^2}{\omega_\ell^2-1}\right) \ln \omega_\ell + \frac{2Y_o}{\sqrt{3}} + \Delta P + P_c$$

This simplifies to

$$\frac{P_f}{Y_o} = \frac{2}{\sqrt{3}} \left(\frac{\omega^2-1}{\omega_\ell^2-1}\right) \frac{\omega_\ell^2}{\omega^2} \ln \omega_\ell - \frac{E\varepsilon_{tc}}{1.7Y_o} \left(\frac{\omega^2-\omega_\ell^2}{\omega^2}\right)^* \quad (18)$$

Equation (18) is plotted in figure 2 for various values of ω_ℓ. ω was assumed to be 5. Shown for comparison are the $\omega_\ell = 1.3$ and $\omega_\ell = 1.7$ of figure 1. The dotted horizontal portions of each curve represent the maximum pressure the liner will hold unsupported, i.e., the autofrettage pressure, and the value of $E\varepsilon_{tc}/Y_o$ where this occurs.

It is apparent (see figure 2) that autofrettaged loose liner construction provides considerable gain over the non-autofrettaged loose liner system. Such an autofrettaged liner construction, of course, will not sustain the magnitude of pressure $P/Y_o = 1.108$ that a cylinder of $\omega = 5$ will withstand if autofrettaged. Nevertheless, the autofrettaged loose liner method appears to provide a low-cost method of barrel replacement with the capability of providing high-pressure operation.

For comparison purposes, the example cited in the second section of this report yields the following results:

Monobloc - non-autofrettaged ($\omega = 5$), $P_f = 77,500$ psi

Loose Liner - non-autofrettaged ($\omega_\ell = 1.3$), $P_f = 52,500$ psi

------

* For $\omega \gg \omega_\ell$, this becomes $\frac{P_f}{Y_o} = \frac{2\omega_\ell^2}{\sqrt{3}} \frac{\ln \omega_\ell}{\omega_\ell^2-1} - \frac{E\varepsilon_{tc}}{1.7Y_o}$ which is a good approximation for all $\omega > 4$.

Monobloc – autofrettaged (ω = 5), P_f = 155,000 psi

Loose Liner – autofrettaged (ω_ℓ = 1.3), P_f = 74,400 psi

For this example, the autofrettaged loose liner has approximately the same capability as the non-autofrettaged monobloc system.

As another example, suppose that it is desired to hold a pressure of 100,000 psi. If the liner has a yield strength of 150,000 psi, P_f/Y_o = 0.667. From figure 2 the following table results:

ω_ℓ	$\dfrac{E \varepsilon_{tc}}{Y_o}$	$10^3 \times \varepsilon_{tc}$	Diametral (I.D. of barrel = 1.00") Clearance (Thousandths)
1.3	0.08	.4	.52
1.5	0.265	1.32	1.98
1.7	0.445	2.22	3.77

Since ease of assembly is required, a minimum of .002" (and preferably .003) diametral clearance would be desirable. Thus, the liner should be selected with a wall ratio somewhere between 1.5 and 1.7.

CONCLUSIONS

The autofrettaged loose liner construction offers distinct advantages over the conventional loose liner construction since considerably higher pressures can be contained elastically. In practice, the manufacture of a system utilizing this method would be as follows:

1. For the desired pressure capability select a yield strength for the liner. Note that this yield can be made somewhat higher during manufacture than it can for a large wall monobloc since the liner wall will be relatively thin. With the computed value of P_f/Y_o read off $E \varepsilon_{tc}/Y_o$ from figure 2 for various wall ratios of the liner.

2. Compute the diametral clearance for each liner. Based upon the manufacturing capabilities available, select a reasonable value for this clearance, thereby selecting the required liner.

3.   Have the liner manufactured, heat treated and autofrettaged to the pressure given by equation (9). Then finish ground to the dimensions desired. (As little material as possible should be removed in this process to avoid reducing the residual stresses.)

4.   Design the jacket to have the same approximate I.D. as the O.D. of the liner. Finish machine the I.D. to the O.D. of liner plus the required clearance. (In the development of the equations in the first and second sections of this report no attention was given to the stresses developed in the jacket. This was not an oversight since the jacket can always be designed to have a higher pressure capability than the liner by means of autofrettage.)

With this procedure the system is then ready for operation. The liners can be replaced with little difficulty provided the design pressure is not exceeded.

At the Naval Ordnance Laboratory, the 1,000-ft. Hyperballistics Range No. 4 contains a barrel having a 1.5-inch bore and an 8-inch outside diameter. It was designed for pressures in excess of 100,000 psi. The original cost of this barrel (which is the cost of replacing it) was $35,000. Cost estimates, using the autofrettaged loose liner construction outlined above, show that liners, capable of providing operation up to 100,000 psi, can be constructed for about $2,000. The indicated cost saving makes the use of this construction method extremely attractive.
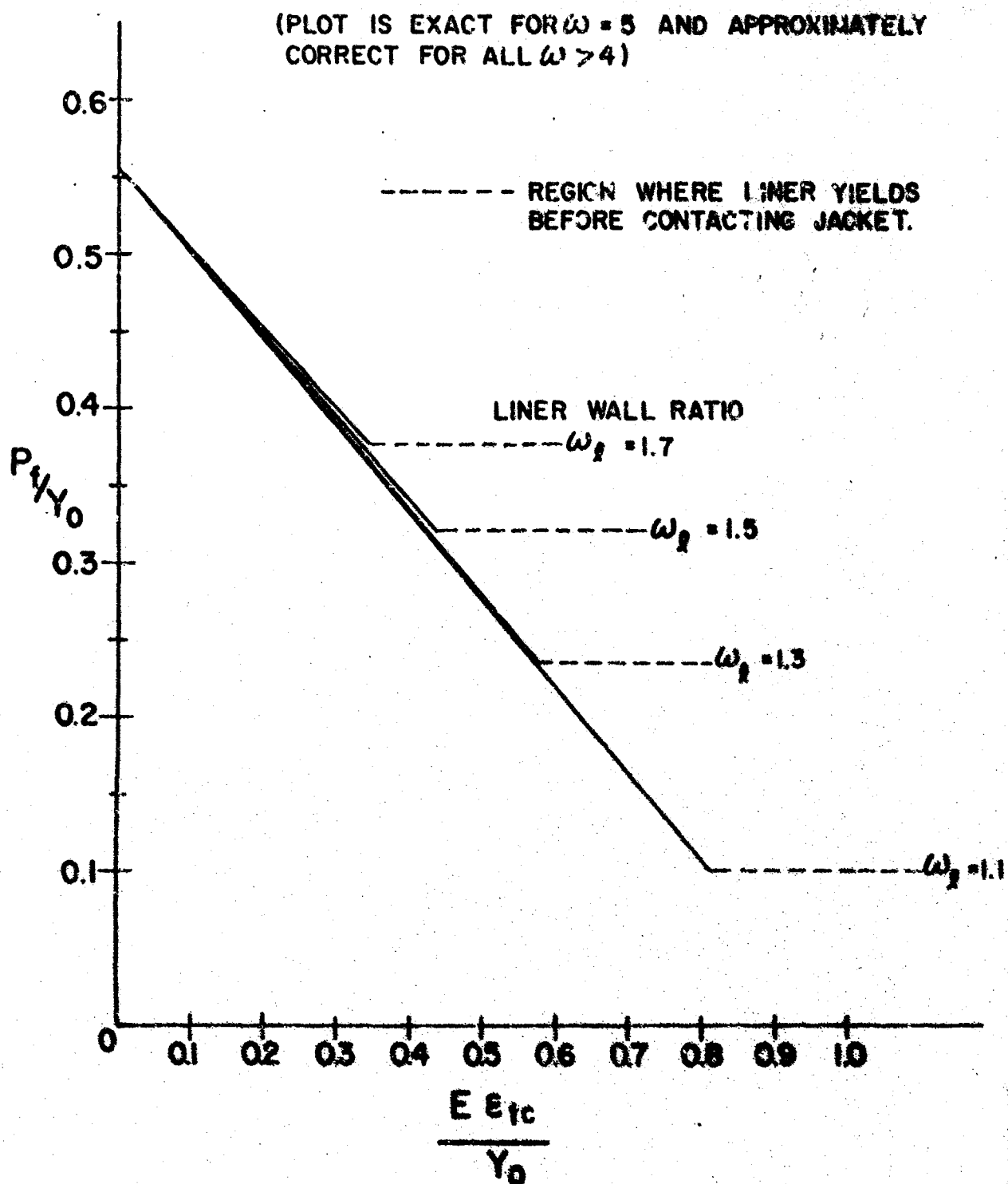
(PLOT IS EXACT FOR $\omega = 5$ AND APPROXIMATELY CORRECT FOR ALL $\omega > 4$)

- - - - - REGION WHERE LINER YIELDS BEFORE CONTACTING JACKET.

LINER WALL RATIO

$\omega_\ell = 1.7$

$\omega_\ell = 1.5$

$\omega_\ell = 1.3$

$\omega_\ell = 1.1$

P_ℓ / Y_0

$\dfrac{E \, \varepsilon_{tc}}{Y_0}$

FIG. 1 INTERNAL PRESSURE REQUIRED TO YIELD LINER AS A FUNCTION OF INITIAL LINER – JACKET CLEARANCE.
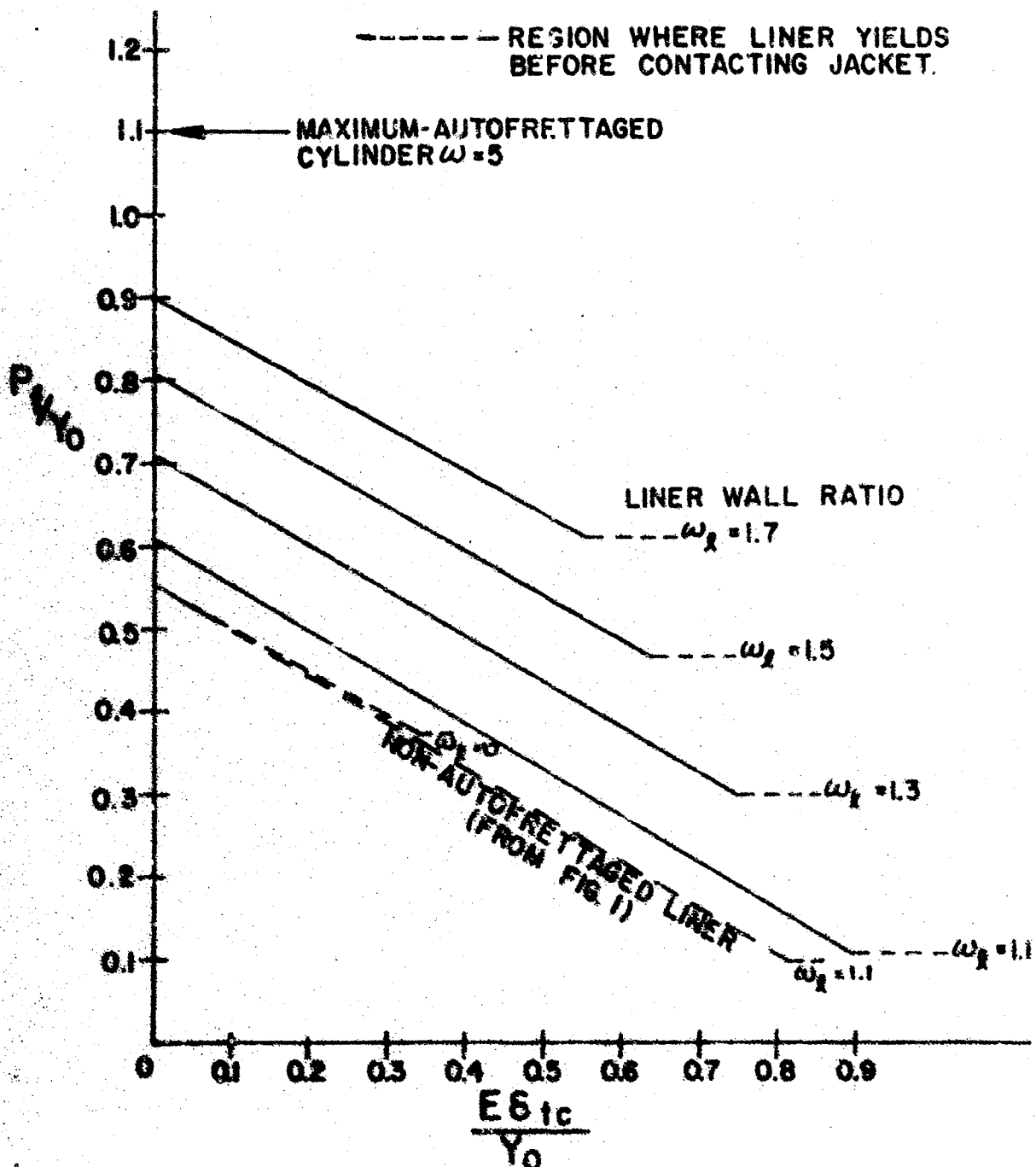
FIG. 2 INTERNAL PRESSURE REQUIRED TO YIELD A FULLY AUTOFRETTAGED LINER AS A FUNCTION OF INITIAL LINER CLEARANCE.

CATALOGING INFORMATION FOR LIBRARY USE

BIBLIOGRAPHIC INFORMATION

		CODES	DESCRIPTORS	CODES
SOURCE	NOL technical report	NOLTR	Unclassified - 21	UØ21
REPORT NUMBER	63-78	63ØØ78	SECURITY CLASSIFICATION AND CODE COUNT	
REPORT DATE	15 May 1963	Ø563	CIRCULATION LIMITATION	
			CIRCULATION LIMITATION ON BIBLIOGRAPHIC	
			BIBLIOGRAPHIC (SUPPL, VOL, ETC.)	

SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Autofrettaged	AUTFR	High-speed	HIGS		
Liners	LINR	Low	LOWE		
Hypervelocity	HYPV	Firing	FIRI		
Launchers	LAUN	Life	LIFE		
Gun barrels	GUNB	Replacement	RPLA		
Reduction	REDC	Construction	CONS		
Cost	COST	Launching	LAUC		
Wear	WEAR	Tubes	TUBE		
Erosion	EROS	Loose	LOOS		
High	HIGH				
Muzzle	MUZZ				
Velocities	VELC				